IET Generation, Transmission & Distribution

Research Article

Power quality enhancement by coordinated operation of thyristor switched capacitor and optimal reclosing of circuit breakers

ISSN 1751-8687
Received on 16th June 2014
Revised on 16th December 2014
Accepted on 24th December 2014
doi: 10.1049/iet-gtd.2014.0613
www.ietdl.org

Sagnika Ghosh ✉, *Mohd. Hasan Ali*

Department of Electrical and Computer Engineering, University of Memphis, Memphis, TN 38152, USA
✉ *E-mail: sghosh2@memphis.edu*

Abstract: This study proposes a new method of power quality enhancement by using the combined operation of thyristor switched capacitor (TSC) and optimal reclosing of circuit breakers in a multi-machine power network. To evaluate the effectiveness of the proposed method, its performance is compared with that of the combined operation of thyristor-controlled braking resistor (TCBR) and optimal reclosing of circuit breakers. The total kinetic energy-based optimal reclosing method is considered. To analyse the effectiveness of the proposed technique, the IEEE nine-bus power system model is considered. Both balanced and unbalanced temporary and permanent faults at different locations in the power system model are considered. Simulation results demonstrate that the proposed TSC together with the optimal reclosing method performs well. Moreover, the performance of the proposed method is better than that of the combination of TCBR and the optimal reclosing method.

1 Introduction

The fitness of electrical power generation to the consumer devices is described by power quality. Synchronisation of the voltage, frequency and phase allows electrical systems to function in their intended manner without significant loss of performance [1]. The reliability and cost of any electrical system depends greatly on the quality of the power supplied to and consumed by the system. Poor power quality may result in improper function, overheating, accelerated wear and tear, falsely tripped circuit breakers and, in some cases, hazardous conditions [2]. Deterioration of power quality because of steady-state disturbances such as harmonics, faults, voltage sags and swells has been extensively experienced. To ensure constant voltage and frequency to the consumers, power quality should be improved and maintained at a desired level. There are numerous types of power quality issues and power problems each of which might have varying and diverse causes. Some of the power quality issues are transients, over-voltage, under-voltage, sag, swell, voltage imbalance, voltage fluctuation, voltage interruption, voltage notching, harmonics, noise and voltage spikes [3–5].

Power quality issues should be resolved to make the power source meet an international standard. Power quality problems can occur at four levels of the system that delivers electric power to the power plants and the entire area transmission system, transmission lines, major substations, distribution substations, primary and secondary power lines, and distribution transformers and service equipment and building wiring [6].

There are several methods to mitigate the power quality issues such as surge suppressors, dynamic voltage restorer, line reactor, isolation transformers, voltage regulators, power conditioners, uninterrupted power supply, proper wiring and grounding [7].

A thyristor switched capacitor (TSC) is a type of equipment used for compensating reactive power in electrical power systems [8–14]. On the other hand, conventional auto-reclosing of circuit breakers can affect the stability and power quality of the system, as it is dependent on the generator state of reclosing instances. Hence, to enhance the power quality and transient stability, circuit breakers should be closed at an optimal reclosing time, when the system disturbance has no effect after reclosing operation [15].

In this paper, in order to improve the power quality of the grid system, a new method by using the combined operation of TSC and optimal reclosing of circuit breakers is proposed. Moreover this is the originality of the work. Also, in order to see how much effective the proposed method is, its performance is compared with that of the combined operation of thyristor-controlled braking resistor (TCBR) and optimal reclosing of circuit breakers. The total kinetic energy-based optimal reclosing of circuit breakers [16] is adopted.

To analyse the power quality enhancement, the IEEE nine bus power system model is considered. Two types of disturbances in the system, such as balanced and unbalanced temporary and permanent faults at different locations in the power system model are considered. Two indices, namely the voltage index and the total harmonic distortion (THD) are used to evaluate the power quality of the system.

The organisation of this paper is as follows. Section 2 describes the model system for the proposed study. Section 3 explains the control methodology. Section 4 describes the total kinetic energy-based optimal reclosing method. Section 5 describes the simulation results. Section 6 discusses about the cost effectiveness of the proposed method. Section 7 explains about the practicality of the proposed method. Finally, Section 8 provides some conclusions regarding this work.

2 Description of model system

For the analysis of the proposed methodology for power quality enhancement, the IEEE nine-bus power system model [17] shown in Fig. 1 is used. The model system consists of two generators (G1 and G2) with capacities of 200 and 130 MVA, respectively, and an infinite bus. Generators are connected to one another through transformers and double-circuit transmission lines. The line parameters have the form $R + jX(jB/2)$, where R, X and B represent resistance, reactance and susceptance per phase with two lines, respectively. F1, F2 and F3 are considered as fault positions. The automatic voltage regulator and governor control models [17] have been considered in this work. The system base is 50 Hz and 100 MVA. Moreover, various parameters of the generators used in this work are described in [17]. The control methods (TSC/TCBR) are added between bus 2 and bus 7 across the G1 terminal.

© The Institution of Engineering and Technology 2015

Elearnica
Downloaded from http://www.elearnica.ir

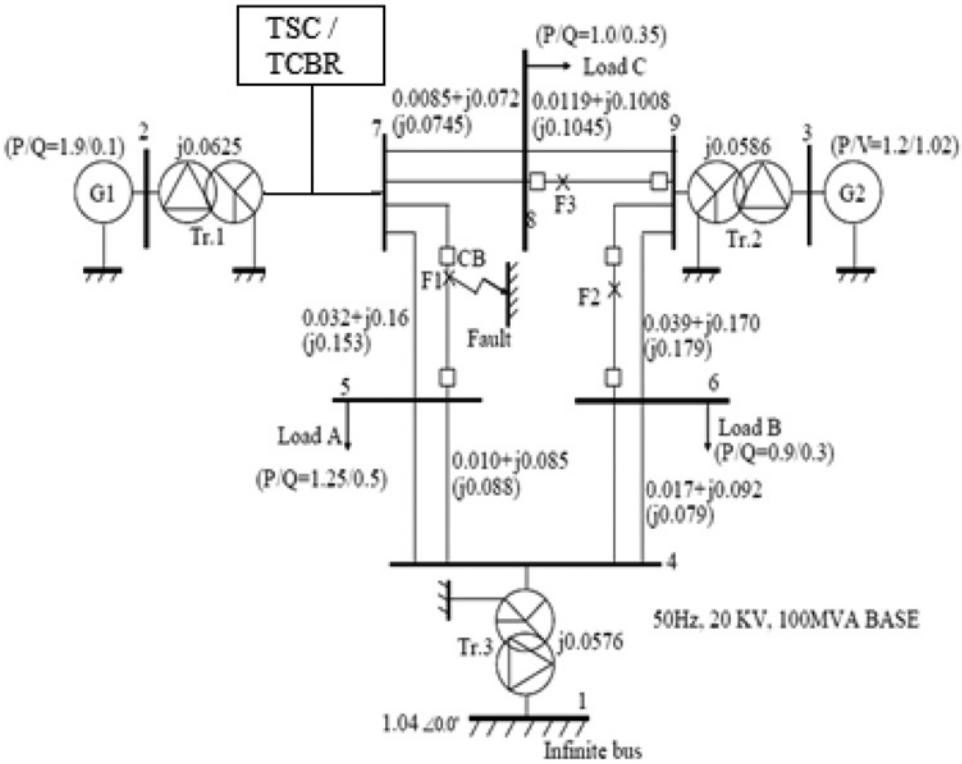

Fig. 1 *IEEE nine-bus power system model*

3 Control methodology

Although there are a lot of control methods used for the power quality enhancement, still it is a matter of interest to explore new control options. In this work, a TSC together with the optimal reclosing of circuit breakers is proposed to improve the power quality of the multi-machine power network.

3.1 Thyristor switched capacitor

A TSC consists of a power capacitor connected in series with a bidirectional thyristor valve [8, 18] and usually, a current limiting inductor (reactor). The function of the TSC reactor is to limit the peak current and rate of rise of current (d*i*/d*t*) when the TSC turns on at an incorrect time. The TSC reactor is usually located outside, close to the main capacitor bank. The thyristor valve typically consists of 10–30 inverse-parallel-connected pairs of thyristor connected in series. The inverse-parallel connection is needed because most commercially available thyristors can conduct current in only one direction. For some low-voltage applications, it may be possible to avoid the series connection of thyristors; in such cases, the thyristor valve is simply an inverse-parallel connection of two thyristors. Here, the TSC is connected in parallel to the line as an additional support in cases of faults. It consists of a high value of capacitor which is usually switched with the help of back-to-back thyristors as shown in Fig. 2. The reactive power capacity of the capacitor, *C*, used is 50 Mvar. Here, it is operating only when the error percentage is more than 2% between the reference and terminal voltages. Thyristors work as a switching device for controlling the switching of the capacitor. Alpha is the switching pulse of the thyristors in Fig. 2, which is generated according to the control structure employed in Fig. 3.

The control block diagram of TSC, as shown in Fig. 3, consists of a classical proportional–integral–derivative (PID) controller and a limiter. The controller takes the change in voltage of synchronous generator, Δv, as an input, and fed its output to the limiter block. A limiter is used to limit the output of PID controller within the range L_{min} and L_{max} as required. The PID controller parameters shown in Table 1 are determined by trial and error method for optimising the best system performance. The final control output from the controller block is fed to the thyristor respective switch. Finally, alpha is generated from the limiter block, which is the switching pulse of the thyristors shown in Fig. 3.

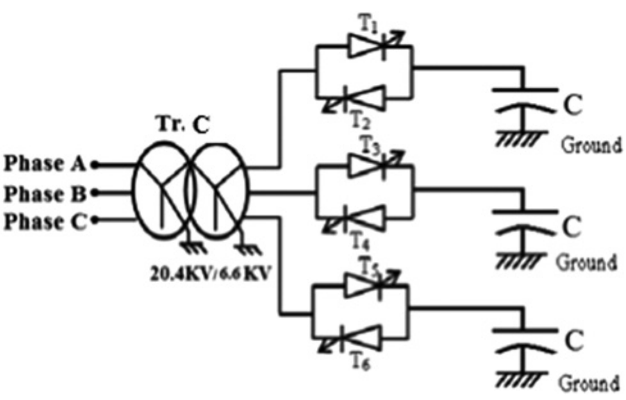

Fig. 2 *Single line diagram of TSC model*

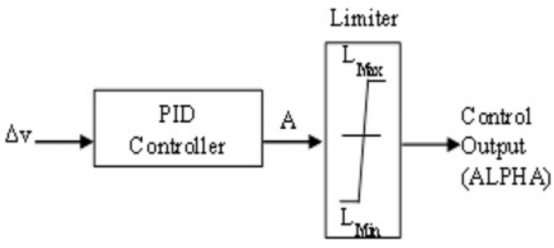

Fig. 3 *Control block diagram of TSC*

© The Institution of Engineering and Technology 2015

Table 1 Values of PID controller parameters

Model type	K_p	T_i	T_d	Limiter	
				L_{max}	L_{min}
TSC	100	0.01	10	180	0
TCBR	100	0.1	10	180	0

3.2 Thyristor-controlled braking resistor

In this work, in order to evaluate the effectiveness of the proposed TSC method together with the optimal reclosing in more detail, its performance is compared with that of the combination of TCBR and optimal reclosing. The barking resistor is a dummy load that is added in the power grid system during any transients occurring in the system. It not only improves the transient stability of the given electric power grid, but also helps in the bulk power transmission without going out of synchronism. It is switched-in at the terminal of the electrical machine such as synchronous generator, to decrease the accelerating speed of the generator as required by the given system, and is switched-out after getting the desired speed. It can be connected in series or in parallel with the given system depending on its purpose such as improving the dynamic stability, low-voltage ride through induction machines and so on. The TCBR model, as shown in Fig. 4, consists of two controlled thyristors connected back-to-back in series with the single braking resistor unit, BR, which is grounded, for a per phase system.

Fig. 4 shows the three-phase configuration for the TCBR control which is connected to the main grid system through step-down transformer (Tr.-BR). The back-to-back connected thyristors are acting as a controlling switch for the braking resistor model, hence the firing angle, α, for this circuit varies between 0° and 180°. Thyristors T1, T3 and T5, shown in Fig. 4, are forward-biased, so they operate for positive half of voltage cycle and the thyristors T2, T4 and T6, shown in Fig. 4, are reverse-biased and hence operate for the negative half of voltage cycle. Following a fault, current flows through the BR unit, if the thyristors T1, T3 and T5 or thyristors T2, T4 and T6 are in ON states. It decreases the accelerated power by consuming excessive transient energy.

For the TCBR model switch, the firing angle, α, is 0° for full conduction of BR unit. By solving the power equation (1) for $\alpha = 0$, the resistance of BR unit, R_{BR}, can be derived [19]

$$P_{BR} = \frac{1}{\pi}\int_0^{\pi} v i_R d(\omega t) = \frac{V_g^2}{\pi R_{BR}}(\pi - \alpha + 0.5\mathrm{Sin}(2\alpha)) \quad (1)$$

Multiple inputs such as rotor angle, voltage, speed, power and so on, from the synchronous generator can be given to the controller for designing a better braking resistor model [20, 21].

In this work, change in voltage of the synchronous generator (i.e. the total voltage at transient state−the total speed at steady state), Δv, is considered as an input to the controller, and respective output is generated.

The control strategy used for the TCBR is the same as the TSC control method as in Fig. 3. The only difference is the value of the PID parameters shown in Table 1. The value of the each phase resistance used in TCBR method is 0.4356 Ω.

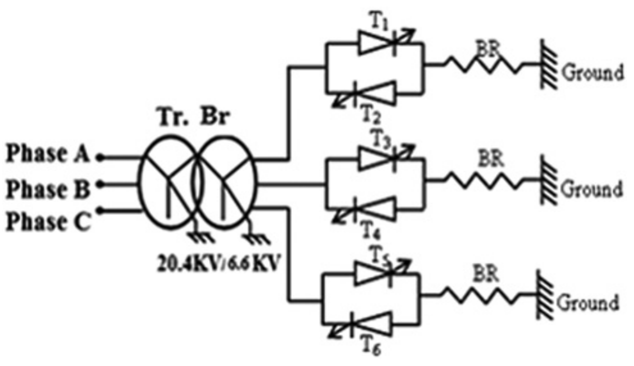

Fig. 4 *Single line diagram of TCBR model*

Table 2 Optimal reclosing time for temporary and permanent faults

Fault type	Fault point	OPRT (s) for temporary fault	OPRT (s) for permanent fault
Three-line-to-ground (3LG)	F1	0.889	0.889
	F2	0.870	0.871
	F3	0.873	0.873
Single-line-to-ground (1LG)	F1	0.810	0.810
	F2	0.850	0.800
	F3	0.848	0.729

4 Total kinetic energy-based optimal reclosing method

As already explained, in this work, the total kinetic energy-based optimal reclosing technique is adopted [15, 18]. The optimal reclosing time is considered as the point which meets the following conditions:

(i) The point when the total kinetic energy oscillation of the generators without reclosing operation becomes the minimum.
(ii) The value obtained from condition (i) must be greater than T_{CB} (reclosing time) [15] as shown below

$$T_{CB} = \left(10.5 + \frac{KV}{34.5}\right)\text{cycles} \quad (2)$$

where KV indicates the line-to-line rms voltage of the system.

Otherwise, the next minimum time of the kinetic energy response in condition (i) should be chosen.

In this work, the system frequency is 50 Hz, where 1 cycle = 20 ms, therefore the value of T_{CB} is 0.223 s.

This method uses the kinetic energy of each generator, which can be obtained easily. The total kinetic energy, W_{total}, (3) can be calculated by knowing the rotor speed of each generator and is given by

$$W_{total} = \sum_{i=1}^{N} \frac{1}{2} J_i \omega_{mi}^2(J) \quad (3)$$

where w_{mi} is the rotor angular velocity in mechanical rad/s, i is the generator number, N is the total number of generators and J_i is the moment of inertia in kg m^2 which includes the machine power ratings and inertia.

Values of optimal reclosing time (OPRT) of different fault positions for temporary and permanent faults are calculated from the total kinetic energy responses and are represented in Table 2. In this case, the OPRT values are certainly bigger than the T_{CB} value in order to allow for the arc to extinguish.

5 Simulation results

Simulations are performed through the Matlab/Simulink software. Both balanced and unbalanced types of faults are considered. It is assumed that the fault occurs at 0.1 s, the circuit breaker opens at 0.2 s and the circuit breaker recloses at the OPRT mentioned in Table 2. In case of permanent faults, the circuit breakers reopen after 0.1 s of the optimal reclosing instances.

© The Institution of Engineering and Technology 2015

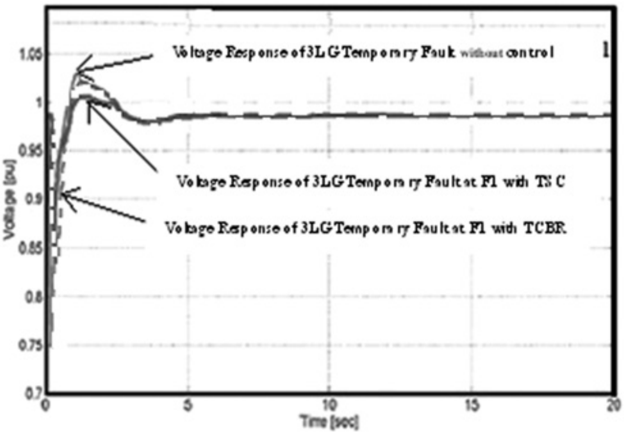

Fig. 5 *Generator terminal (G1) voltage responses of 3LG temporary fault at F1*

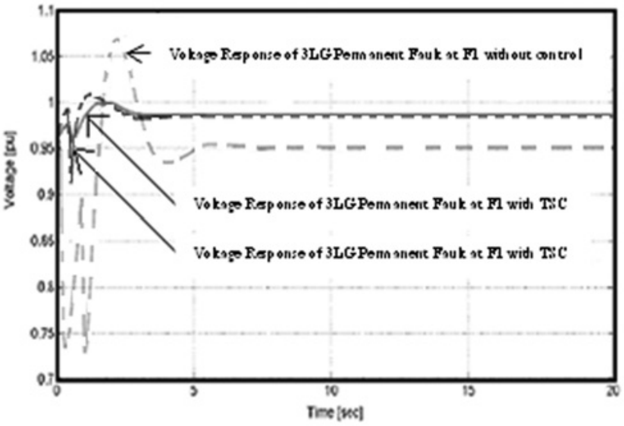

Fig. 6 *Generator terminal (G1) voltage responses of 3LG permanent fault at F1*

Figs. 5–8 show the voltage responses for 3LG and 1LG temporary and permanent faults at F1 point. The graphs show three voltage responses; one is without control, the other one with the combined TSC and optimal reclosing method, and the third one with the TCBR together with the optimal reclosing. From the responses, it is seen that the proposed TSC together with the optimal reclosing method works well to improve the power quality. However, the

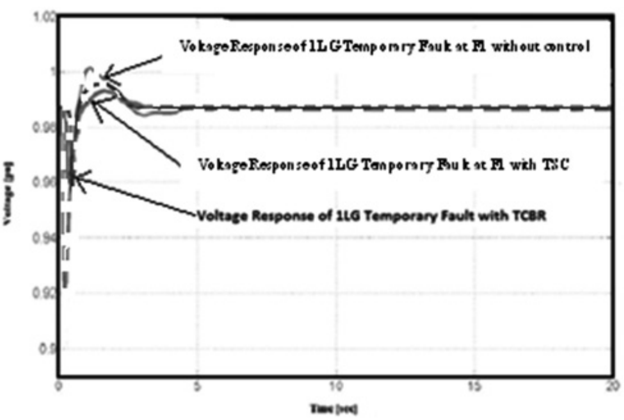

Fig. 7 *Generator terminal (G1) voltage responses of 1LG temporary fault at F1*

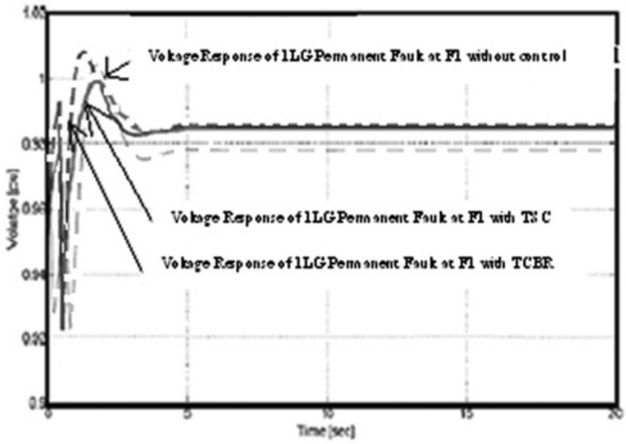

Fig. 8 *Generator terminal (G1) voltage responses of 1LG permanent fault at F1*

performance of the proposed method is better than that of the combination of TCBR and optimal reclosing.

To evaluate the effectiveness of the proposed method in more detail, an index, namely voltage index, V_{index} shown below in (4) is considered

$$V_{\text{index}} = \int_0^T |\Delta V| \, dt \tag{4}$$

where ΔV indicates the total voltage deviation of the generators, and T is the simulation time of 20.0 s. The lower the value of the index, the better the system performance is.

5.1 Power quality analysis in terms of voltage index, V_{index}

Tables 3 and 4 show the values of voltage indices for temporary and permanent 3LG and 1LG faults at points F1, F2 and F3 with and without the TSC and TCBR control methods. From the indices, it is clear that the proposed TSC together with the optimal reclosing is effective in improving the power quality. It is also evident from the indices that the proposed method is better than the combination of TCBR and optimal reclosing. It is important to note here that, since the studied system has only two synchronous generators, the improvement of the power quality is limited, as evident from the index values of Tables 3 and 4. However, if the system becomes very large, the performance without any control will deteriorate much, and the effectiveness of TSC will be visualised more.

5.2 THD analysis

The THD is a measure of the effective value of the harmonic components of a distorted waveform. It is the potential heating value of the harmonics relative to the fundamental. The THD expression shown below in (5) is the summation of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave [22]

$$\text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} \times 100\% \tag{5}$$

where V_1 is the fundamental voltage and $V_2, V_3, \ldots, V_n$ are the higher order harmonic components of the synchronous generator terminal voltage.

Tables 5 and 6 show the values of THD for temporary and permanent 3LG and 1LG faults at points F1, F2 and F3 with and without the TSC and the TCBR control methods. It is evident

© The Institution of Engineering and Technology 2015

Table 3 Values of V_{index} of temporary and permanent 3LG fault with TSC and TCBR control method

Fault type	Fault category	Fault point	V_{index}				
			Without control	With TSC control	% Improvement	With TCBR control	% Improvement
3LG	temporary	F1	1.0510	1.0250	2.4738	1.0405	0.9990
		F2	0.7734	0.6110	20.998	0.7726	0.1304
		F3	0.8416	0.8401	0.1786	0.8407	0.1425
	permanent	F1	1.1370	1.1320	0.4398	1.1356	0.1231
		F2	0.8424	0.8399	0.2967	0.8409	0.1781
		F3	0.8751	0.8719	0.3657	0.8728	0.2628

Table 4 Values of V_{index} of temporary and permanent 1LG fault with TSC and TCBR control method

Fault type	Fault category	Fault point	V_{index}				
			Without control	With TSC control	% Improvement	With TCBR control	% Improvement
1LG	temporary	F1	0.7756	0.7725	0.3997	0.7732	0.3094
		F2	0.7750	0.7698	0.6709	0.7702	0.6065
		F3	0.7751	0.7735	0.2064	0.7741	0.1290
	permanent	F1	0.7903	0.7819	1.0629	0.7856	0.5947
		F2	1.0920	0.7959	27.115	0.7973	26.987
		F3	0.7827	0.7522	3.8968	0.7534	3.7435

Table 5 Value of THD of 3LG temporary and permanent faults

Fault type	Fault category	Fault point	THD without control, %	THD with control, %			
				TSC	% Improvement	TCBR	% Improvement
3LG	temporary	F1	9.42	1.30	8.12	1.70	7.72
		F2	6.88	0.31	6.57	0.78	6.10
		F3	5.03	1.68	3.35	1.95	3.08
	permanent	F1	7.18	4.56	2.62	5.86	1.32
		F2	5.91	4.10	1.81	4.23	1.68
		F3	11.99	2.55	9.44	2.73	9.26

Table 6 Value of THD of 1LG temporary and permanent faults

Fault type	Fault category	Fault point	THD without control, %	THD with control, %			
				TSC	% Improvement	TCBR	% Improvement
1LG	temporary	F1	3.76	0.52	3.24	2.69	1.07
		F2	8.33	4.96	3.37	5.14	3.19
		F3	5.09	0.32	4.77	1.07	4.02
	permanent	F1	21.51	12.58	8.93	14.10	7.41
		F2	6.44	4.44	2.00	4.81	1.63
		F3	5.14	4.12	1.02	4.69	0.45

from the THD values that the effects of harmonics are reduced when the control is used. Moreover, it is clear that the proposed control method is more effective than the combination of TCBR and optimal reclosing method.

6 Practicality of the optimal reclosing method

One question might arise here regarding the practical implementation of the optimal reclosing method. However, it is hoped that the mentioned optimal reclosing method can be implemented in real time. The required signal needed to be captured for the total kinetic energy-based reclosing method is speed. The online measurement of the speed of different generators located at different locations and then calculation of the total kinetic energy can be done through the global positioning system (GPS) [22–26].

Fig. 9 shows the functional block diagram of the mentioned optimal reclosing method including GPS, where the GPS receiver receives the digitalised speed signals collected from the generators, and makes them both time and phase synchronised. Using the computers, the central control office can then determine the OPRT easily.

7 Cost effectiveness

In this work, we were interested in knowing the cost of the proposed TSC. However, we are not aware of the actual cost of the controller. Based on the number of components used, we can say that the cost of the TSC might be more than the TCBR. In the TSC, the main components are the capacitor and the six back-to-back connected thyristors. On the other hand, the main components in the TCBR are the six thyristors and the braking resistor. However, the cost of capacitor might be higher than that of the braking resistor. Although the cost of the TSC might be higher than that of the TCBR, the percentage improvement with respect to the voltage index and the THD shows that the thyristor-controlled capacitor

© The Institution of Engineering and Technology 2015

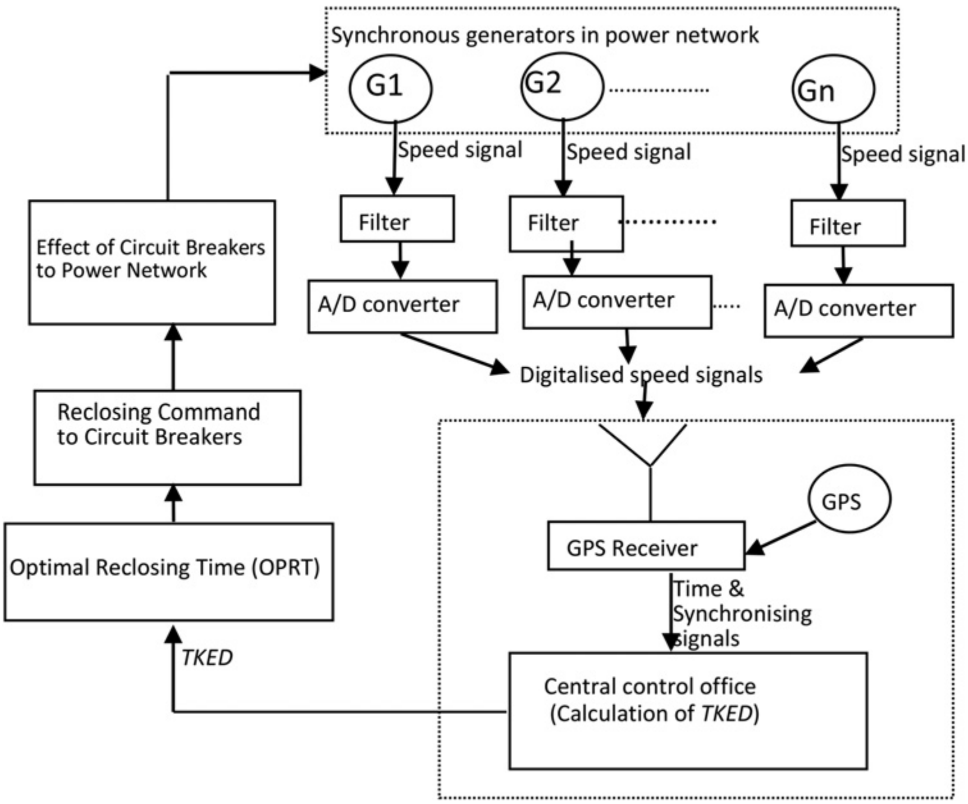

Fig. 9 *Closed-loop control system of the optimal reclosing method including GPS function*

can be implemented to improve the power quality of the power system.

8 Conclusion

This paper proposes the combined operation of optimal reclosing of circuit breakers and TSC to enhance the power quality in a multi-machine power system. Based on the simulation results of balanced and unbalanced temporary and permanent faults and the THD, the following points are noteworthy:

(a) The proposed thyristor-controlled capacitor together with the optimal reclosing is effective to enhance the power quality of the system.
(b) The performance of the proposed method is better than that of the combination of TCBR and optimal reclosing.

Therefore the combined operation of the total kinetic energy-based reclosing technique and the thyristor-based capacitor is considered as an effective tool to enhance the power quality of a multi-machine power system.

In our future work, we will consider the integration of renewable energy systems, such as wind and photovoltaic generation systems, into a large power system model consisting of synchronous generators, and analyse the power quality issues. Moreover, communication delays arising from cyber attacks or cyber hacking during online calculation of the total kinetic energy will also be considered. Furthermore, suitable means to minimise the negative effects of communication delays will be explored.

9 References

1 Bollen, M.H.J.: 'Understanding power quality problems: voltage sags and interruptions' (IEEE Press, 2000)
2 Dugan, R.C., McGranaghan, M.F., Santoso, S., Beaty, H.W.: ''Electrical power systems quality' (McGraw-Hill, 2003, 2nd edn.)
3 Morcos, M.M., Anish Ibrahim, W.R.: 'Electric power quality and artificial intelligence: overview and applicability', *IEEE Power Eng. Rev.*, 1999, **19**, (6), pp. 5–10
4 Bhattacharyya, S., Cobben, S.: 'Consequences of poor power quality – an overview', 2011
5 Gupta, S.: 'Power quality: problems, effects and economic impacts', *Int. J. Electr. Electron. Eng. (IJEEE)*, 2012, **1**, (1), pp. 83–91
6 Khalid, S., Dwivedi, B.: 'Power Quality Issues, Problems, Standards & their effects in industry with corrective means', *Int. J. Adv. Eng. Technol.*, 2011, **1**, (2), pp. 1–11
7 Al-Haddad, K., Singh, A.C.B.: 'A review of active filters for power quality improvement', *IEEE Trans. Ind. Electron.*, 1999, **46**, (5), pp. 960–971
8 Fotuhi-Firuzabad, M., Faried, S.O., Billinton, R.: 'Power system reliability enhancement using a thyristor controlled series capacitor', *IEEE Trans. Power Syst.*, 1999, **14**, (1), pp. 369–374
9 Goyal, A., Kapil, N., Mahapatra, S.: 'Implementation of thyristor switched capacitors for power factor improvement', *Adv. Electron. Electr. Eng.*, 2014, **4**, (3), pp. 225–230, ISSN 2231-1297
10 Subrahmanyam, J., Reddy, S.R., Sahoo, P.K., Sashidhar, C., Reddy, N.M.: 'A novel method for improvement of power factor using thyristor switched capacitor in wind mill power station', *Int. J. Emerg. Technol. Adv. Eng.*, 2012, **2**, (2), ISSN 2250-2459
11 Ohtake, A., Zhang, F., Fujimoto, T., Nakayama, N.: 'Development of 200-Mvar class thyristor switched capacitor supporting fault ride-through'. Int. Power Electronics Conf. (IPEC-Hiroshima 2014-ECCE-ASIA), 2014, pp. 3857–3863
12 Zhang, L., Qi, S.-C., Zhao, H.-G., Yao, J.: 'Study of TSC plus SVG based on the mixture of hot rolling mill control of reactive power compensation'. Int. Conf. on Control, Automation and Systems Engineering (CASE), 2011, pp. 1–4
13 Ebrahimi, S., Najmi, V., Mokhtari, H.: 'Reactive compensation investigation of TSC systems based on different power factor definitions'. IECON 2012 – 38th Annual Conf. on IEEE Industrial Electronics Society, 2012, pp. 1393–1398
14 Su, H., Li, Q.: 'Rough controlling TSC for reactive current compensation in traction substations'. Fifth Int. Power Electronics and Motion Control Conf. (IPEMC), CES/IEEE, 2006, pp. 1–5
15 Ali, M.H., Murata, T., Tamura, J.: 'Effect of coordination of optimal reclosing and fuzzy controlled braking resistor on transient stability during unsuccessful reclosing', *IEEE Trans. Power Syst.*, 2006, **21**, (3), pp. 1321–1329
16 Yagami, M., Murata, T., Tamura, J.: 'An analysis of optimal reclosing for enhancement of transient stability', *Electr. Eng. Japan*, 2004, **147**, (3), pp. 32–39
17 Ghosh, S., Ali, M.H.: 'Load angle based optimal reclosing technique of circuit breakers for power quality enhancement'. Paper ID: 55, Proc. of the IEEE SoutheastCon 2013, Florida, USA, 4–7 April 2013
18 Roy, B., Sherif, O.F., Fotuhi-Firuzabad: 'Subtransmission system reliability enhancement using a thyristor controlled series capacitor', *IEEE Trans. Power Deliv.*, 2000, **15**, (1), pp. 443–449
19 Ali, M.H., Murata, T., Tamura, J.: 'Influence of communication delay on the performance of fuzzy logic-controller braking resistor against transient stability', *IEEE Trans. Control Syst. Technol.*, 2008, **16**, (6), pp. 1232–1241

© The Institution of Engineering and Technology 2015

20 Trofimenko, D.Ye.: 'The stability of a hydro – electric generator with electric braking'. Electric Technology U.S.S.R., August 1962, vol. 1

21 Hartley, R.H., Croft, W.H.: 'Improving stability by use of dynamic braking', *Power Appar. Syst., III, Trans. Am. Inst. Electr. Eng.*, 1962, **81**, (3), pp. 17–24

22 APT Associated Power Technologies: Total harmonic distortion and effects in electrical power systems

23 Working Group H-8 of the Relay Communications Subcommittee of the IEEE Power System Relaying Committee: 'IEEE standard for synchrophasors for power systems', *IEEE Trans. Power Deliv.*, 1998, **13**, (1), pp. 73–77

24 Li, H.Y., Southern, E.P., Crossley, P.A., *et al.*: 'A new type of differential feeder protection relay using the global positioning system for data synchronization', *IEEE Trans. Power Deliv.*, 1997, **12**, (3), pp. 73–77

25 Working Group H-7 of the Relaying Channels Subcommittee of the IEEE Power System Relaying Committee: 'Synchronized sampling and phasor measurements for relaying and control', *IEEE Trans. Power Deliv.*, 1994, **9**, (1), pp. 442–452

26 Burnett, R.O.Jr., Butts, M.M., Cease, T.W., *et al.*: 'Synchronized phasor measurements of a power system event', *IEEE Trans. Power Deliv.*, 1994, **9**, (3), pp. 1643–1650

© The Institution of Engineering and Technology 2015